USE OF SWARM INTELLIGENCE IN SPACECRAFT CONSTELLATIONS FOR THE RESOURCE EXPLORATION OF THE ASTEROID BELT

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ABSTRACT

We describe the Prospecting ANTS Mission (PAM) whose object is to explore the resource potential the Solar System's Asteroid Belt. The mission, set about 20-30 years in the future, is consistent with the present NASA strategic plan for the HEDS (Human Exploration and Development of Space) enterprise. In this plan, the automated discovery of space resources is envisioned as a building block for expanding the human presence in space.

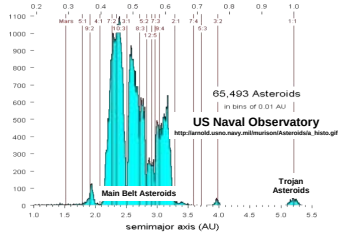
The Main Belt Asteroids are Central to NASA Themes
- **Space Science Origins**
- **Human Exploration and Development of Space**

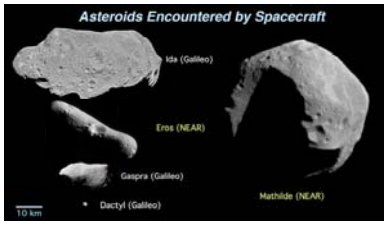
Main Belt Asteroids
- ~ 10^5-10^6 objects (>1km diameter)
- Between the orbits of Mars and Jupiter (2.1 AU – 3.3 AU)
- Surface of largest 1000 observed asteroids is ~ 70% the area of Mars. The remainder may dwarf the surface area of the Earth.

Asteroid Resources
- Refractory (Fe, Ni, Si) materials dominate inner belt
- Volatiles (NH4, CH4, H2O) abundant in outer belt

Asteroid Science
- Wide range of processes and history represented
- Processed material and primordial material

Distribution of Observed Asteroids





The Main Belt Asteroids are a challenging target.
- Thousands of destinations
  - ⇒ complex mission planning and trajectories
- Far from Earth and the Sun
  - ⇒ communication/control latencies & bandwidth
  - ⇒ weaker Solar constant
- Most are small and dark
  - ⇒ hard to find
- Irregular shape
  - ⇒ complex observation requirements
- Irregular, rotating mass distribution
  - ⇒ irregular, rotating gravity field
  - ⇒ complex encounter and orbital dynamics

Requirements to prospect thousands of asteroids a year
- Deep space operations far from Earth and Sun
- One month of optimal science operations at each asteroid
- Full suite of science instruments deployed at each asteroid
- Concurrent operations at hundreds of asteroids
- No single point of failure
- Robust to minor faults and catastrophic failures
- Optimal operations in spite of mission attrition

⇒ ***Multiple, specialized, redundant spacecraft***
Autonomous operations at many levels
-- from swarm to spacecraft to subsystem

ANTS Mission Architecture
- Specialized spacecraft
  - Division of labor
  - Optimal operations
- Cooperation to achieve mission goals
  - Insect colony analog of social behavior

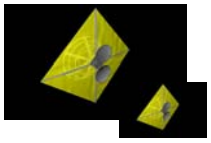
Prospecting ANTS Mission
- A swarm of specialized spacecraft
  - Single instrument Sciencecraft Workers
  - Messenger/Rulers for Comm & Control
- Hierarchical Insect-colony analog
  - Swarm-level mission directed behavior
  - Sub-swarm
    - regional coverage, resource sharing
  - Team/Worker-group
    - coordinated science operations
  - Individual behaviors and autonomy
  - Sub-individual, systems & subsystems

PAM Spacecraft
- Highly autonomous
- Solar sail propulsion
  - *High agility, exceptional control*
- No consumables
- Pico-spacecraft ~ 1 kg
- Constructed at Libration point habitat
- Mission function optimized
  - Workers: Specialized science
    - Imaging, Spectrometry, Gravimetry
  - Messenger/Rulers
    - Communications & Control
    - Data processing & archival
    - Mission goal & operations mgmt.

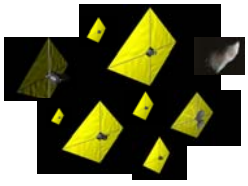
Artist's Concept of the Prospecting ANTS Mission

AUTONOMOUS NANO-TECHNOLOGY SWARM

PROSPECTING ANTS MISSION

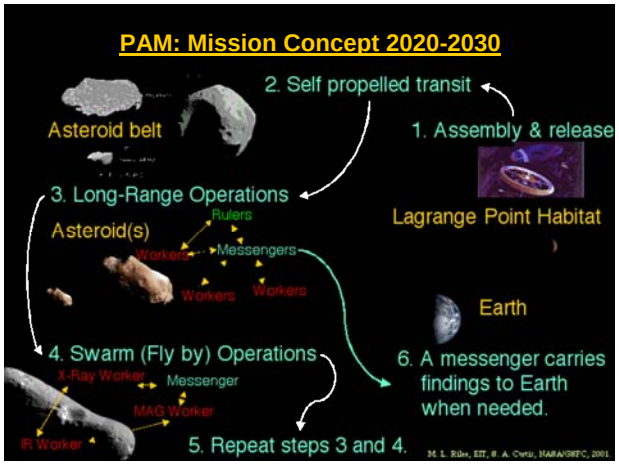


MESSENGER/RULERS
Enhanced Computation
Enhanced Communication
Enhanced Data Storage
Responsible for mission goals
Provide command & communication network

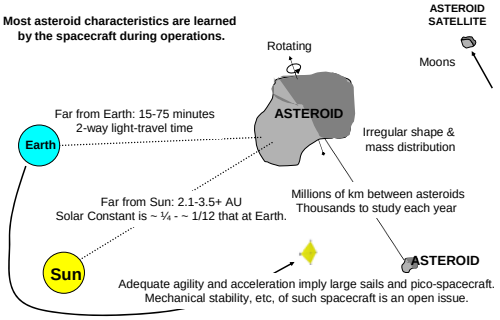


WORKERS
Specialists in a science instrument
Responsible for science operations
Form teams for asteroid encounters

Both classes built on an autonomous spacecraft architecture providing basic functions (GN&C, ACS…).

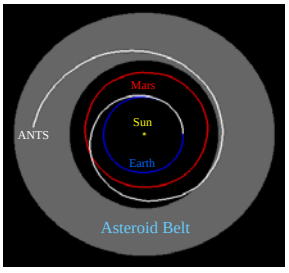


PAM Challenges for low thrust Solar Sail spacecraft

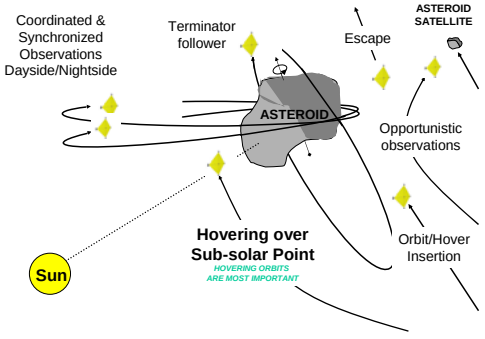


PAM Transfer Architecture

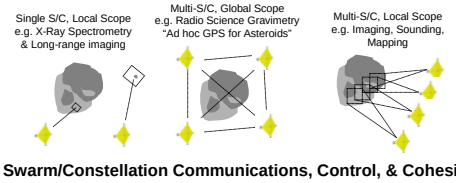
- Solar sail size: 100 m²
- S/C Mass: 1 kg
- Flat plate normal from sun line: 30°
- Transfer to: 2.8 AU
- Transfer time: 3.5 yr.
- da/dt~100 Mm/12 hrs.



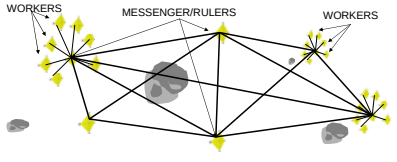
PAM Encounter Architecture



Autonomous, Optimized Science Operations



Swarm/Constellation Communications, Control, & Cohesion



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